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Mice intravenously infected with an immunising dose of the gram-positive  
bacterium, Listeria monocytogenes, produced circulating interferon (IFN) during  
the inductive phase of the anti-Listeria immune response. In addition to  
inducing IFN, the Listeria also dramatically altered the host's responsiveness to  
IFN inducing agents. Within 24 hours of infection, mice acquired a 50-fold  
greater than normal capacity to produce the alpha and/or beta IFN classes (IFN $\alpha/\beta$ )  
following intravenous injection of endotoxin. Serum IFN  $\alpha/\beta$  levels peaked by  
2 hours after which, high-levels of gamma IFN (IFN $\gamma$ ) were detected in the sera

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of Listeria-infected animals given the B cell mitogen. Similar studies carried out with the interferon inducing agent polyinosinic-polycytidylic acid (Poly(I)-Poly(C)) which, like endotoxin, induces peak levels of serum IFN 2 hours after intravenous injection, revealed that 24 hour infected mice produced only 4-8 times more IFN <sup>alpha</sup> than non-infected mice. However, unlike endotoxin, Poly(I)-Poly(C) did not elicit IFN <sup>gamma</sup> synthesis in Listeria-infected animals.

alpha Beta gamma

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## Annual Report

In addition to antiviral activity, the three antigenically distinct species ( $\alpha, \beta, \gamma$ ) of interferon (IFN) exhibit multiple biological activities, some of which suggest possible immunomodulatory roles for these molecules in either the generation and/or expression of immunity. The ultimate objective of our research is to determine the function of each IFN in cell-mediated immunity. The response of mice to Listeria monocytogenes offers an excellent model for studying the possible roles for IFNs in preimmunity resistance and acquired specific resistance to a facultative intracellular pathogen. The expression of anti-Listeria resistance is dependent upon the generation of activated macrophages capable of expressing microbicidal function. Last year, we reported IFN $\gamma$  is capable of activating macrophages, and earlier studies from this laboratory established a striking parallel between the development of T cell-mediated anti-Listeria immunity and an enhanced ability of spleen cells from responding mice to produce IFN $\gamma$  in response to T cell polyclonal mitogens. Collectively, these findings strongly suggest a role for IFN $\gamma$  in the expression of anti-Listeria resistance. During the past year, we have documented the IFN responses of mice during the course of an immunizing Listeria infection, and now are preparing to undertake studies which will examine the roles of each Listeria-induced IFN in the host's defense against bacterial infection.

### 1. IFN Responses of Listeria-Infected Mice

The serum IFN titers in endotoxin-injected and non-injected mice at progressive times following an immunizing dose of Listeria monocytogenes ( $2 \times 10^3$  viable organisms) are presented in Figure 1. Twenty-four hours after Listeria inoculation, low levels of IFN were detected in the serum. The Listeria-elicited serum IFN titers peaked (32 units) on the second day, and by the fifth day of infection, no IFN activity was detected. Listeria also dramatically enhanced the host's ability to produce IFN in response to the intravenous injection of endotoxin. Serum IFN levels measured 2 hours after endotoxin injection revealed that as early as 8 hours following Listeria inoculation, infected mice acquired the capacity to produce 5 times more endotoxin-induced IFN than non-infected animals. Maximum endotoxin-induced IFN titers occurred 24 hours following Listeria inoculation, with infected mice producing 64-fold more serum IFN activity than normal. Subsequent to this time, the enhanced responsiveness of the Listeria-infected mice to produce endotoxin-induced IFN slowly declined.

### 2. Temporal Appearance of Endotoxin-Induced Serum IFN

The kinetics of appearance for endotoxin-induced IFN in the sera of normal mice and mice inoculated with Listeria 24 hours earlier are presented in Figure 2. Maximum IFN levels were detected in the sera of both groups of animals 2 hours after the intravenous administration of 25  $\mu$ g of endotoxin. At this time, the serum of the Listeria-infected mice possessed 32 times more IFN activity than serum of normal mice. These studies also revealed that endotoxin-induced IFN was detected earlier and the titers were significantly higher at all intervals in the sera of Listeria-infected mice than in normal animals. Two endotoxin-induced IFN responses were observed in the sera of normal mice. Following the initial serum IFN response, which was complete after 3 hours, a second minor peak of serum IFN activity was observed at 12 hrs. An examination of the descending portion of the serum IFN curve for the Listeria-infected mice revealed a slight upward inflection in the curve between 3-6 hrs. Evidence will be presented later showing this is due to a second endotoxin-induced IFN response.

### 3. Endotoxin and Poly(I)·Poly(C) Dose-Responses

Endotoxin-induced IFN dose-response studies carried out in 24 hour Listeria-infected and normal mice are presented in Figure 3, panel A. Graded concentrations of endotoxin were intravenously injected into groups of both animals. Two hours later, the mice were bled and the sera assayed for IFN activities. The dose-response curves established that mice infected one day earlier with an immunizing dose of Listeria, were at least 50 times more responsive to IFN induction by endotoxin than normal animals. Interferon levels plateaued in the infected animals treated with concentrations of endotoxin over 1µg, where the titers of IFN were at least 50-fold greater than that of normal mice given the highest concentration of endotoxin (100µg) tested.

Since the synthetic polyribonucleotide Poly(I)·Poly(C) also induces peak serum IFN levels 2 hours after intravenous injection, it was deemed of interest to compare the relative responsiveness of Listeria-infected mice to Poly(I)·Poly(C) IFN induction in a dose-response study (Fig. 3, panel B). The Poly(I)·Poly(C) dose-response curves for IFN induction in normal and 24 hour Listeria-infected mice exhibit similar slopes. Moreover, although the Listeria-infected animals proved more responsive to Poly(I)·Poly(C), the yields of IFN elicited by all concentrations were only 4-8 fold higher than those produced by similarly treated normal mice.

### 4. Endotoxin-Induced IFN in Spleen Cultures Derived from Listeria-Infected Mice

The spleen is a source of endotoxin-induced serum IFN (3,4,14). Therefore, studies were carried out to determine the responsiveness of spleen cells obtained from Listeria-infected mice to produce IFN after endotoxin stimulation. Spleen cell cultures were established from normal mice and from mice either inoculated 1 or 6 days earlier with Listeria. The cultures were incubated with endotoxin (5µg/ml) and at the designated times, portions of the media were collected and assayed for IFN activity (Fig. 4). Spleen cells obtained from mice infected 1 day earlier with Listeria, produced the highest levels of endotoxin-induced IFN activity. These cultures also produced IFN earlier (2hrs) than either of the two other experimental groups of spleen cells. The endotoxin-induced spleen cultures of both normal and 6 day-infected mice did not secrete IFN until after 2 hours. However, like cultures from 1 day-infected mice, peak levels of IFN in normal cultures were attained by 6 hours, whereas cultures from 6 day-infected mice continued producing IFN after this time.

### 5. The Requirement of Viable Listeria for Augmented IFN Induction

The foregoing studies established that an immunizing dose of viable Listeria could elicit IFN, as well as enhance the responsiveness of the infected mice to IFN inducing agents. In Table 1, are presented the findings of studies designed to determine if by increasing the number of inoculated organisms would further enhance the yields of endotoxin-induced IFN, and whether viable Listeria are required for the enhanced endotoxin-induced IFN response. Increasing the Listeria inoculum 100 times over the usual immunizing inoculum resulted in only a marginal 2-fold increase in serum IFN activity in mice receiving endotoxin 2 hrs earlier. Listeria rendered non-viable by either heat or ultraviolet irradiation were incapable of invoking the augmented endotoxin-induced IFN response observed in animals treated with the same number of viable organisms.

6. T-cell Independence for Enhanced 2 Hour Endotoxin-Induced Serum IFN in Listeria-Infected Mice

Thymectomized, irradiated, and bone marrow reconstituted (TXB) AB6F<sub>1</sub> mice or congenitally athymic (nu/nu) mice of BALB/c background were infected with  $2 \times 10^5$  viable Listeria and 24 hours later injected intravenously with endotoxin. Two hours later, the sera from the Listeria-infected and similar groups of non-infected mice were collected and assayed for IFN (Table 2). The infected TXB AB6F<sub>1</sub> and athymic nude mice produced significantly higher yields of serum IFN 2 hours after endotoxin induction than their respective non-infected control groups. However, the differences in magnitude of the IFN responses between non-infected and infected T cell-deficient groups were not as great ( $\sim 50\times$ ) as those previously observed between infected and normal AB6F<sub>1</sub> immunocompetent mice. This was due to the fact that the non-infected T cell-deficient mice produced relatively more endotoxin-induced IFN than non-infected AB6F<sub>1</sub> immunocompetent mice.

7. Interferon Responses to Different Agents at Progressive Times Post Listeria Inoculation.

The IFN responses of mice to three agents were determined at times prior to, after, and at the peak of the anti-Listeria T cell-mediated immune response on day 6. Two and 6 hours following the intravenous injection of endotoxin, Poly(I)·Poly(C), or  $10^6$  viable Listeria, the various groups of mice were bled and the sera assayed for IFN (Table 3). Peak 2 hour endotoxin-induced IFN levels occurred 1 day following an immunizing Listeria dose, after which, the early 2 hour IFN response gradually declined by day 15 to a level still 10 times higher than normal. In contrast to the peak 2 hour endotoxin-induced IFN response, which occurred 1 day following Listeria inoculation, the maximum 6 hour serum IFN response elicited by endotoxin occurred on day 6. On the sixth day, the 6 hour serum IFN titer was equivalent to the earlier 2 hour serum titer, which was only 4-fold lower than the peak 2 hour response observed in mice 1 day after Listeria inoculation. However, the 6 hour serum IFN levels produced by mice injected with Listeria 15 days earlier, were greatly diminished relative to the 2 hour IFN titers detected in these mice. The 2 and 6 hour Poly(I)·Poly(C)-induced serum IFN levels were elevated only on day 1 of Listeria infection. The highest 2 and 6 hour serum IFN titers induced by injection of  $10^6$  viable Listeria, coincided with the peak of anti-Listeria T cell-mediated immunity on the sixth day after injection of an immunizing Listeria dose.

8. Antigenic Analysis of Endotoxin-Induced and Poly(I)·Poly(C)-Induced Serum IFNs

The availability of anti-murine IFN $\alpha/\beta$  neutralizing serum and monoclonal anti-murine IFN $\gamma$  neutralizing antibody, enabled the qualitative and quantitative analysis of the IFN $\alpha/\beta$  and IFN $\gamma$  activities present in endotoxin-induced or Poly(I)·Poly(C)-induced serum IFN samples (Table 3). It should be stated that as in the human IFN system, the murine IFN $\alpha$  and IFN $\beta$  molecules are antigenically distinct not only from one another, but also from IFN $\gamma$ . Specific anti-murine IFN $\alpha$  and IFN $\beta$  neutralizing antibodies are not available, however, anti-IFN $\alpha/\beta$  is available. Antigenic analyses of the IFN classes (total IFN $\alpha/\beta$  or IFN $\gamma$ ) existing in the various endotoxin-induced or Poly(I)·Poly(C)-induced serum IFN samples (Table 3), were performed by reacting each sample with an excess ( $>500$  neutralizing units) of anti-IFN $\alpha/\beta$  or anti-IFN $\gamma$  antibody, as well as with a mixture of both antibodies. The reacted samples were then assayed for non-neutralized antiviral activities. The results of these studies revealed that the Poly(I)·Poly(C)-induced antiviral activities in all sera tested were mediated exclusively by IFN $\alpha/\beta$  (Table 4). Likewise, IFN $\alpha/\beta$  mediated the antiviral activity in the 2 hour sera of endotoxin-induced mice. However, the later

appearing 6 hour endotoxin-induced serum IFN molecules produced by mice infected 1 and 6 days earlier with Listeria, were mixtures of IFN $\alpha/\beta$  and IFN $\gamma$ . Based on the antiviral activity remaining after the antibody treatments, IFN $\gamma$  is the major IFN species in these 6 hour sera.

These studies establish that shortly after an immunizing dose of Listeria, mice acquire a greatly augmented capacity to produce endotoxin-induced IFN $\alpha/\beta$ , and following the peak IFN $\alpha/\beta$  response, IFN $\gamma$  is produced. The capacity of Listeria-infected mice to produce elevated IFN $\alpha/\beta$  titers in response to endotoxin is long lived and diminishes slowly, as evidenced by the significantly higher IFN $\alpha/\beta$  titers produced by mice infected 15 days earlier, as compared to normal mice. The capacity of Listeria-infected mice to produce IFN $\gamma$  following induction with the B cell mitogen is more transitory, peaking along with anti-Listeria immunity on day 6, and is lost 15 days after inoculation with Listeria.

Figure 1

Listeria-induced and endotoxin-induced serum interferon levels during infection. Listeria-induced IFN serum levels (□--□) and serum IFN levels measured 2 hours post intravenous injection of 25  $\mu$ gs of endotoxin (O--O) in mice at progressive time following inoculation of an immunizing Listeria dose.

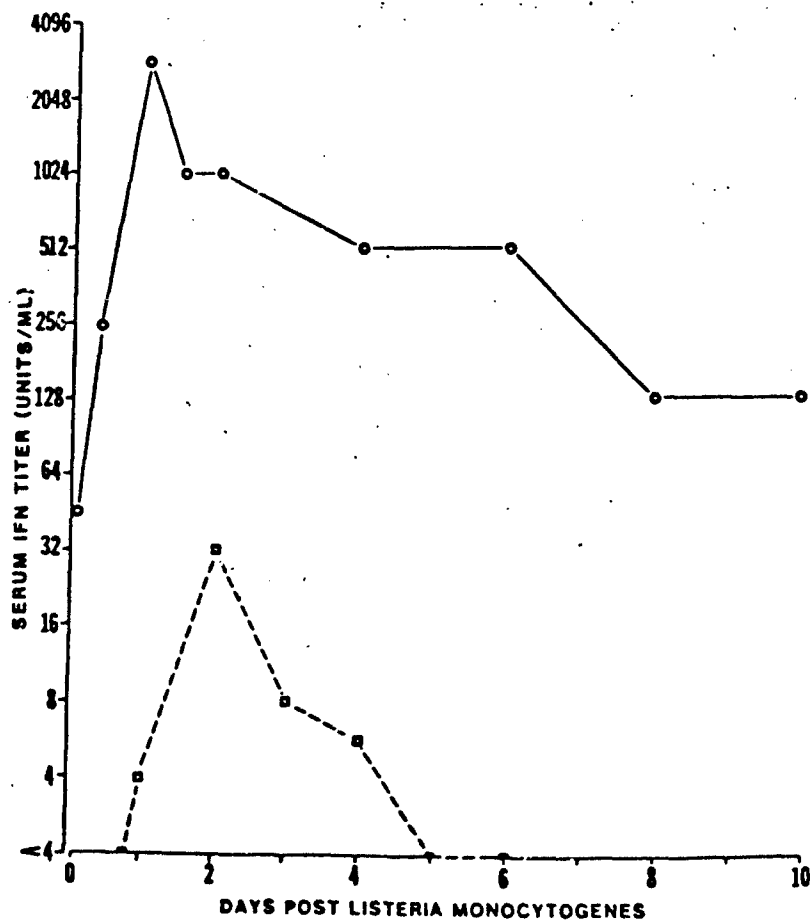


Figure 2

Kinetics of IFN appearance in the sera of normal and 1 day Listeria-infected mice. Groups of normal and 1 day Listeria-infected mice were injected intravenously with 25  $\mu$ gs of endotoxin (0 hr) and bled at the indicated times.

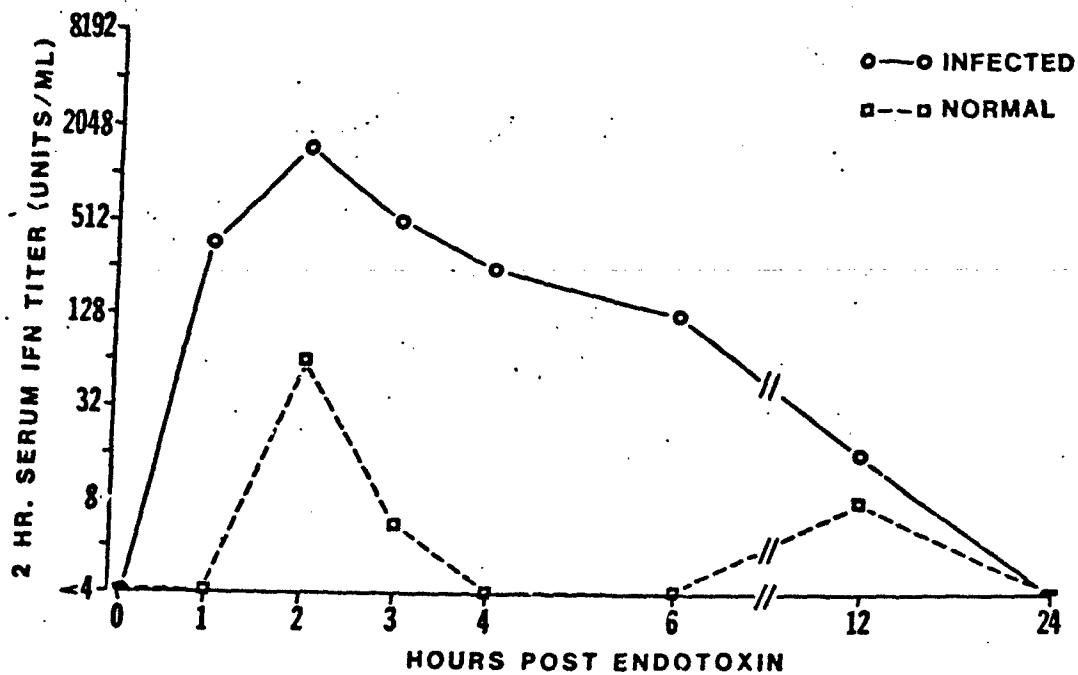




Figure 3

Endotoxin (Panel A) and Poly(I)·Poly(C) (Panel B) induced serum IFN levels in normal and 1 day *Listeria*-infected mice. Groups of 5 mice were injected intravenously with the designated concentrations of either IFN inducing agent and bled 2 hours later.

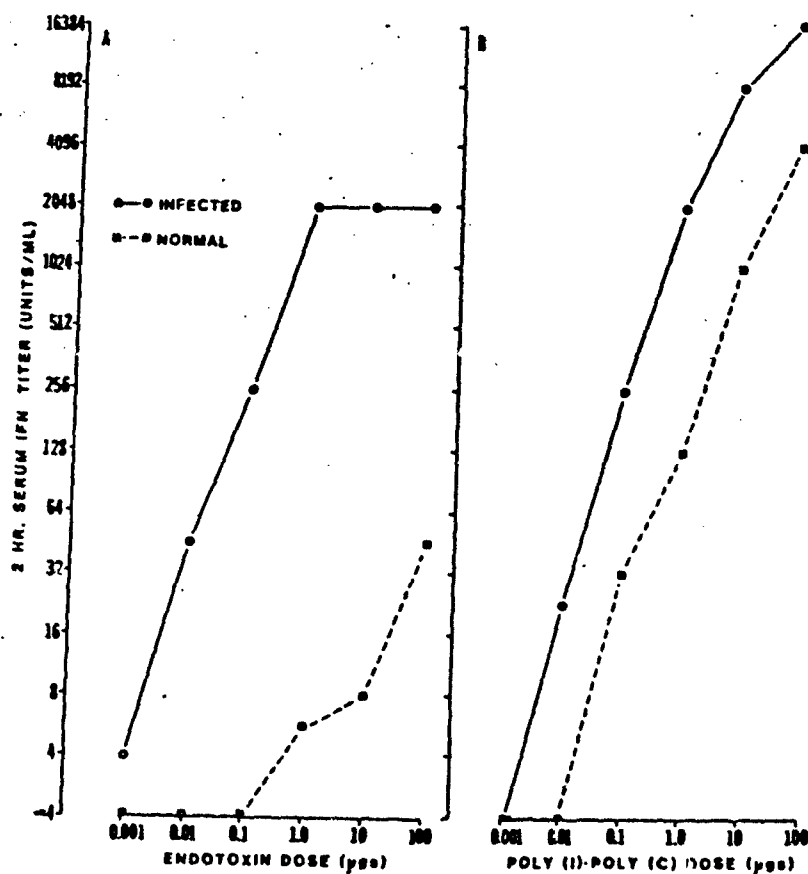


Figure 4

Endotoxin-induced IFN synthesis in spleen cell cultures derived from normal, 1 and 6 day *Listeria*-infected mice. Replicate spleen cell cultures ( $10^7$  cells/ml) were incubated with 5  $\mu$ g/ml of endotoxin at 0 hr and samples of medium collected at the designated times and assayed for IFN activity.

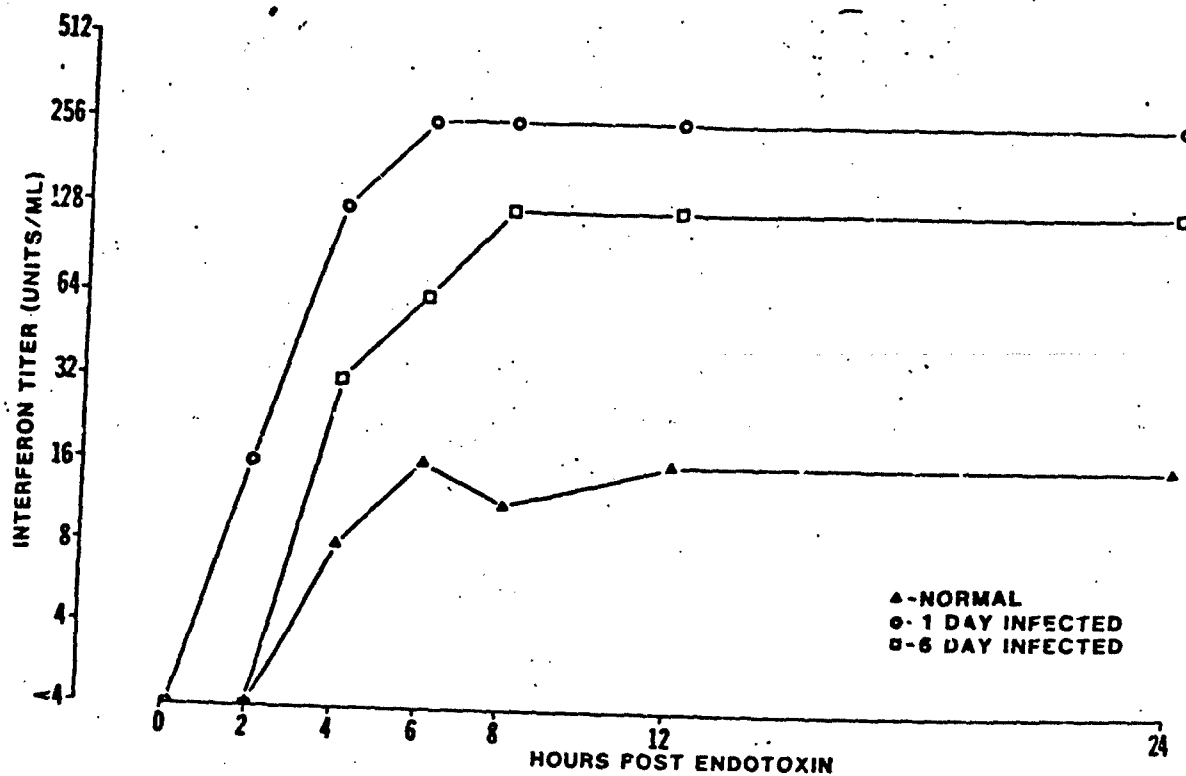


Table 1

Viable *Listeria* are Required for Enhanced  
Endotoxin-Induced Interferon Responses

<u>Treatment 24h prior to endotoxin</u>	<u>Serum inteferon titer(units/ml) 2h post endotoxin<sup>c</sup></u>
None	48
$2 \times 10^3$ viable <i>Listeria</i> , i.v.	2048
$2 \times 10^5$ viable <i>Listeria</i> , i.v.	4096
$2 \times 10^5$ $\Delta$ killed <sup>a</sup> <i>Listeria</i> , i.v.	32
$2 \times 10^5$ U.V. killed <sup>b</sup> <i>Listeria</i> , i.v.	32

<sup>a</sup>Broth culture of *Listeria* incubated at 60°C/1hr. Following such treatment, no viable *Listeria* were detected by plating on trypticase soy agar.

<sup>b</sup>Details of U.V. irradiation procedure presented in Materials and Methods.

<sup>c</sup>Intravenous injection of 25  $\mu$ gs of endotoxin.

Table 2

Enhanced Responsiveness to Endotoxin Interferon Induction in  
TXB and Athymic Nude Mice Following Listeria Infection

<u>Mouse type</u>	<u>Treatment 24h prior to endotoxin</u>	<u>Serum interferon(units/ml) 2h post endotoxin<sup>c</sup></u>
TXB <sup>a</sup>	none	384
"	2x10 <sup>5</sup> <u>Listeria</u> , i.v.	2048
Athymic nude	none	192
"	2x10 <sup>5</sup> <u>Listeria</u> , i.v.	6144

<sup>a</sup>TXB: thymectomized, irradiated, and bone marrow reconstituted AB6F1 mice.

<sup>b</sup>Congenitally athymic nude (nu/nu) mice of BALB/c background.

<sup>c</sup>25 µgs endotoxin injected intravenously.

Table 3

Endotoxin and Poly(I)·Poly(C)-Induced Serum Interferon Levels  
at Various Days Post Listeria Infection

<u>Day of Infection</u>	<u>Inducing agent<sup>a</sup></u>	<u>Serum interferon titers(units/ml) at</u>	
		<u>2 h</u>	<u>6 h.</u>
non-infected	Endotoxin	32	6
	Poly(I)·Poly(C)	2048	192
	<u>Listeria</u>	<4	<4
1 day	Endotoxin	2048	192
	Poly(I)·Poly(C)	8192	2048
	<u>Listeria</u>	4	16
6 day	Endotoxin	512	512
	Poly(I)·Poly(C)	2048	64
	<u>Listeria</u>	32	64
15 day	Endotoxin	384	32
	Poly(I)·Poly(C)	3072	256
	<u>Listeria</u>	<4	6

<sup>a</sup>At 0 h groups of mice were injected with 5 µgs of endotoxin, 25 µgs Poly(I)·Poly(C) or 10<sup>6</sup> viable Listeria.

Table 4

Antigenicities of 2 and 6 hour Endotoxin and Poly(I)·Poly(C)-Induced Serum Interferons Produced by *Listeria*-Infected Mice

Day of infection	IFN inducing agents <sup>a</sup> at 0 h	Hour of serum IFN sample	Antiviral activities (units/ml) <sup>b</sup> after reaction with excess			
			none	anti- $\alpha/\beta$	anti- $\gamma$	anti- $\alpha/\beta$ +anti- $\gamma$
non-infected	Endotoxin	2	64	<8	64	<8
	Poly(I)·Poly(C)	2	512	<8	512	<8
	Poly(I)·Poly(C)	6	256	<8	128	<8
1	Endotoxin	2	512	<8	256	<8
	Poly(I)·Poly(C)	2	128	<8	256	<8
	Endotoxin	6	256	256	96	<8
	Poly(I)·Poly(C)	6	256	<8	256	<8
6	Endotoxin	2	256	<8	128	<8
	Poly(I)·Poly(C)	2	256	<8	128	<8
	Endotoxin	6	256	128	32	<8
	Poly(I)·Poly(C)	6	256	<8	256	<8
15	Endotoxin	2	512	<8	512	<8
	Poly(I)·Poly(C)	2	512	<8	512	<8
	Endotoxin	6	32	<8	32	<8
	Poly(I)·Poly(C)	6	128	<8	256	<8

<sup>a</sup>Endotoxin (5  $\mu$ g) or Poly(I)·Poly(C) (25  $\mu$ g) injected intravenously at 0 h.

<sup>b</sup>Sera Originally with titers >512 (Table 2) were diluted to ~512 units/ml.